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A Simple Method for the Production of Homogeneous Water Drops Down to 1 Micron Radius

by

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ABSTRACT

A simple method for the production of homogeneous water drops down to 2 microns diameter is described. When bubbles of a given size burst at an air-water interface the collapse of the bubble cavity produces an upward moving jet which quickly disintegrates into several small drops. Each of these drops, not necessarily all the same size, rises to a height which is remarkably constant from one bubble to the next. The drop size at each of these heights was found to be equally constant.

Photographs are shown of the drops produced and their remarkable uniformity in size. The size of the drops is controlled by the bubble size, the larger bubbles producing the largest drops.

INTRODUCTION

Those who have used hypodermic needles to produce water drops of a given size for calibration purposes know only too well the difficulty involved in producing drops < about 1 mm diameter. Surface tension considerations require that the bore diameter of the needle be many times less than that of the drop. At such small diameters high pressures are required to force the water through the bore and, as solid materials in the water will clog the tube, the water must be filtered prior to using.

Drops down to 0.2 mm diameter have been produced with hypodermic needles and microburettes by passing a stream of air concentrically around the tip where the drops are being produced (1, 2). In the presence of the air stream the drops are blown free at a diameter far less than they would have in the absence of the air stream. However, even these techniques are inadequate to produce drops < 100 microns diameter. The production of homogeneous clouds of drops < 100 microns has been accomplished by utilizing the centrifugal forces associated with water on spinning discs. With an apparatus utilizing this principle Walton and Prewett (3) produced monodisperse clouds from 15μ to 3 mm diameter. An improved model was capable of extending the lower limit to 6μ (4). An entirely different method for the production of a monodisperse cloud, recently discussed by Vonnegut and Neubauer (5), produces streams of electrified uniform drops of about 0.1 mm diameter by applying potentials of 5 - 10 kv (ac or dc) to liquids in small capillaries. Under some conditions a smoke of particles of about 1μ diameter can be produced.

The present paper will describe a simple method for the production of homogeneous drops from about 500 down to at least 2μ diameter. The experimental setup requires simply a stream of bubbles rising in a beaker of water. The realization that uniform drops could be systematically produced with such a simple apparatus came out of a photographic study (6) of the mechanism of the bursting of bubbles at an air-water interface (7). High-speed photographs conclusively showed that upon the collapse of a bubble a narrow jet rises rapidly from the bottom of the bubble cavity. Within a distance of perhaps one bubble diameter the jet proceeds to break up into 5 or 6 drops, all of which rise to characteristic heights. With the same bubble size these heights are systematically obtained thus indicating the reproducibility of the various drop sizes at different levels.

These phenomena have been studied, in connection with different problems, by other investigators. Stuhlman (7) was interested in the problem of effervescence and was the first to suggest the jet mechanism as being responsible for the production of drops from breaking bubbles. Boyce (9), in connection with studies of the deposition of airborne salt particles on coastal plants, obtained data for the average diameter of drops ejected by bubbles in sea water as a function of bubble size. However, as neither Stuhlman or Boyce studied the breaking bubble mechanism as a source of homogeneous drops it was felt worth-while to present the ideas contained in this paper.

EXPERIMENTAL METHODS

The production of a steady stream of uniform bubbles of any diameter $> 50\mu$ is easily accomplished by forcing air through fine tips produced by drawing out a length of glass capillary tubing. The size of the bubble is, of course, a function of the bore diameter. The smallest bubbles are produced from hair-like tips with an air pressure of approximately 30 psi.

If the bubbles are allowed to rise in distilled water they will break immediately on contact with the surface, providing the surface is clean. It is sometimes necessary to have the glass capillary tip near the surface to prevent the coalescence of bubbles as they rise through the water. However, if both these precautions are observed a uniform and systematic breaking of the bubbles will occur. As each bubble breaks, the upward moving high velocity jet will form and break into a series of droplets. These droplets rise at speeds, estimated both from analysis of high-speed photographs, and by computation, of several hundreds of cm sec^{-1}. The frictional retarding force at such high speeds causes a rapid deceleration and loss of kinetic energy of the drops. For a given bubble diameter each of the drops will rise to a height which is remarkedly reproducible. If a slow drift of air exists over the water surface, the drops will fall at an angle to the vertical. This is illustrated in the photograph of Figure 1a where the bubbles are breaking in rapid succession so that six or more drops from the highest trajectory are simultaneously airborne. This photograph was made at 0.01 sec exposure with the aid of forward scattered light. With smaller bubbles and a higher rate of production one is able to produce drops at such a rate that 30 or more of the drops from the top trajectory are airborne simultaneously.* This simple experiment, with the great uniformity of the settling rates of the drops formed, soon convinces one of the homogenuity of the drop diameters.

RESULTS

Figure 1b is a drawing, based on the photograph of Figure 1a, to show the most probable trajectories of the drops. Note that the trajectories of the second and third drops from the top are represented in the actual photograph by single drops. These drops are sufficiently large and fall back to the surface at such a rate as to prevent more than one drop for each trajectory to be airborne at any one time. The lowest trajectory on the drawing represents a fifth drop which did not happen to be airborne during the brief exposure for the photograph. This drop is the largest of all the drops and even on its downward flight is discernible to the eye only as a streak of light.

A crude estimate of the drop sizes represented by Figure 1a can be obtained with a knowledge of their fall velocities and Stokes Law. The fall velocities were obtained by measuring the vertical component of the streaks, which represents the drops motion during the exposure, and dividing by the exposure time. With the fall velocities of the drops from the four different trajectories thus obtained, Stokes Law can be used, starting with the top trajectory, to obtain drop diameters of 58, 75, 70, and 37 microns respectively. The diameter of the top drop, 58 microns, was compared with some recent measurements (8), made in this laboratory, on the sizes of drops ejected by bubbles bursting in sea water. For the same height of projection, 4 cm, the top drop was calculated to be 43 microns diameter. It may be that differences in the physical-chemical properties of sea and fresh water, such as surface tension, are responsible for the variation in drop size.

The homogenuity of the drops produced by the top trajectory of Figure 1a is illuatrated by Figure 2. This is a photograph

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* These drops are usually invisible to the unaided eye in normal daylight. They are best made visible by viewing against a black background and looking at an angle of about 140° as measured along a strong beam of light.

of the imprints of the drops on an ammonium chloride coated slide. The diameter of the imprints shown in Figure 2 was several times the diameter of the drops. This is probably explained by the high solubility of NH_4Cl in water. Nevertheless, regardless of the ratio between the diameter of the imprints and the drops, the uniformity of the imprints testifies to the remarkable uniformity of the drop size from the top trajectory. The other trajectories produce their own uniform drops but the upper one, being more readily accessible, was preferred as the source of uniform drops in the present study.

The drop diameters and the heights to which they are ejected, is a function of bubble size, and is dependent on whether the bubbles are breaking in sea or distilled water. Figure 3 is a graph of bubble size versus the heights of the ejected drops. The solid lines are the results of measurements in distilled water by Stuhlman (7) who found six drops produced by the majority of bubbles. The dashed line represents some recent measurements of Boyce (9) in sea water. Note that he was concerned only with the top drop. A maximum ejected height is found in each case, with the drops from bubbles in sea water rising higher (for bubbles $> 800\mu$) and reaching a maximum height at a greater bubble diameter than the same bubbles in distilled water.

Boyce (9) has presented experimental data on the diameters of the highest drop ejected by bursting bubbles in sea water as a function of bubble size. The data fit the linear equation $y = 51.5\ x - 3.95$ where x is the bubble diameter in mm and y the drop diameter in microns. The data, however, represent the drop diameter at 83 per cent relative humidity and 21°C. To obtain the diameter when ejected from the bursting bubble one would have to compute the equilibrium size at the temperature and relative humidity (98 per cent) existing over the sea water at the time of ejection. These computations are easily done with the aid of graphs relating density, temperature and saturation vapor pressure with the chlorinity of the water (10). The above equation, while probably correct for large bubbles, cannot possibly hold for bubbles $<$ 77 microns diameter for below this size the equation predicts negative droplet diameters. Inasmuch as the writer has obtained droplets between 2 and 10 microns diameter from bubbles $<$ 77 microns, and as Boyce seemed little concerned with the small bubbles, it is justifiable to limit consideration of this equation to the larger bubbles.

In order to insure a continuous and rapid rate of production of homogeneous drops it is necessary, as was mentioned earlier, to maintain a clean water surface. This becomes more critical as the bubble diameter increases and especially so in the case of bubbling in sea water. Little difficulty is experienced, however, if the bubbles are $<$ about 600 microns and preferably breaking in distilled water. Fortunately, it is the smaller bubbles that are producing the drops in the size range that are beyond the limits of hypodermic needles and it is in this size range that the bubble technique produces homogeneous drops with a high degree of accuracy.

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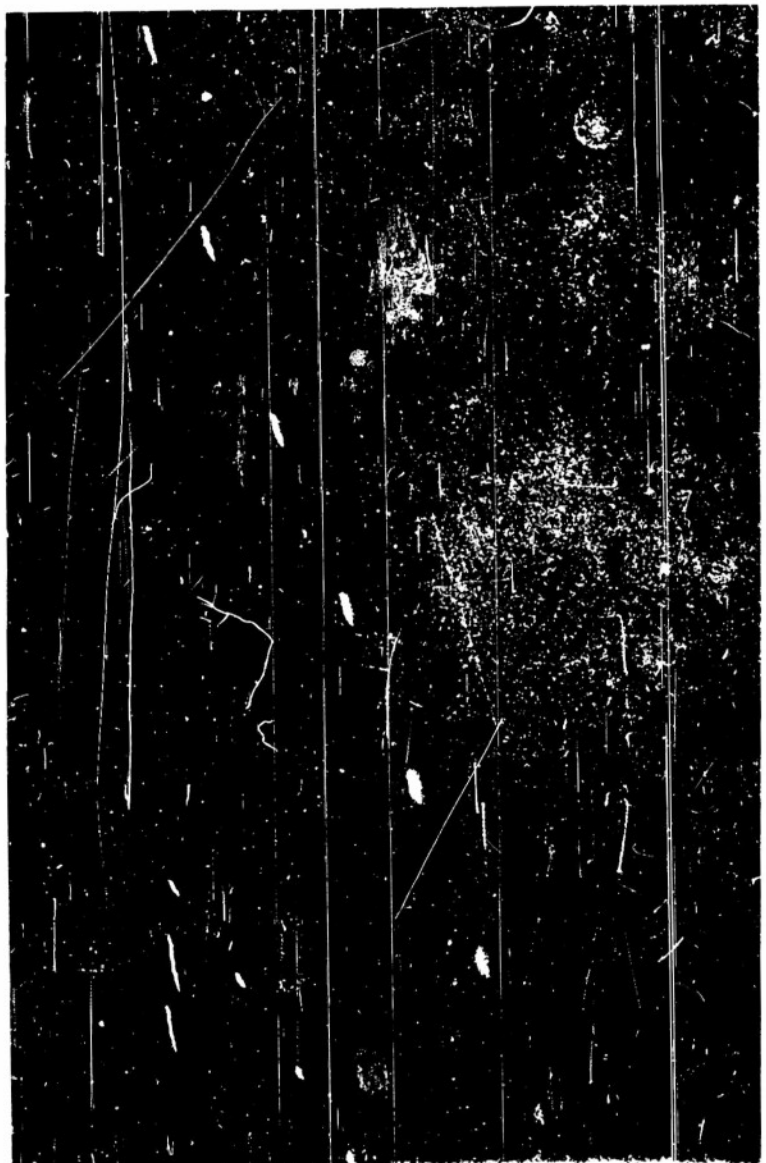

Fig 1a A photograph of the homogenecus drops produced by the breaking of 450 micron diameter bubbles. The length of the streaks, a function of the fall velocity of the drops, is related to the drop diameter.

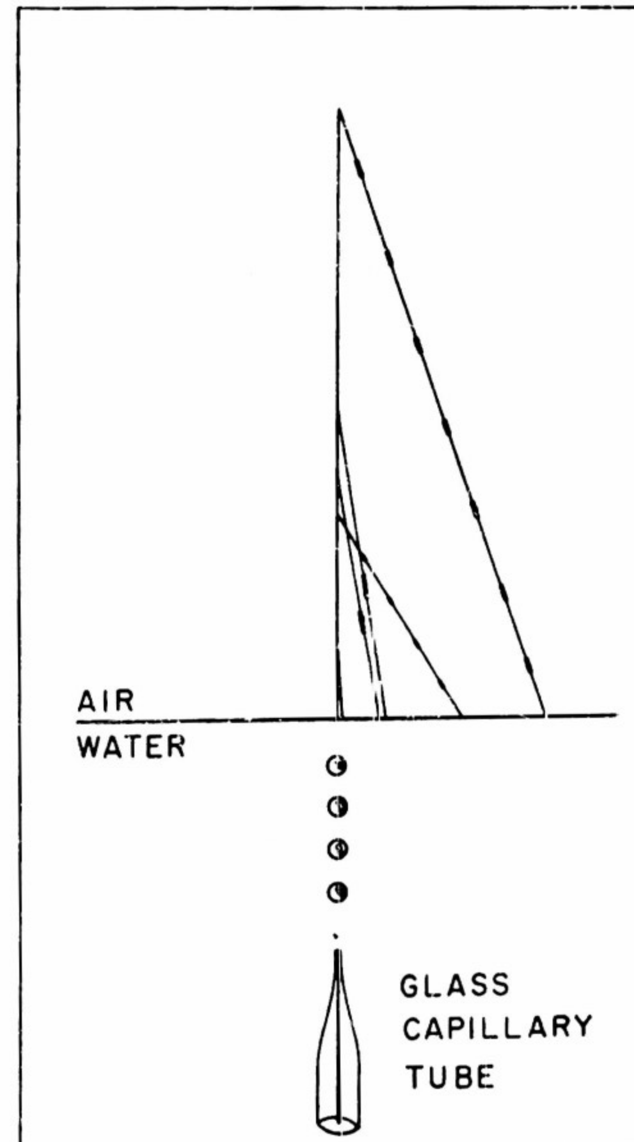

Fig. 1b A drawing based on figure 1a to show the most probable trajectories of the drops. The heavy dashed lines represent the drops as shown in 1a while the light solid lines indicate the trajectories.

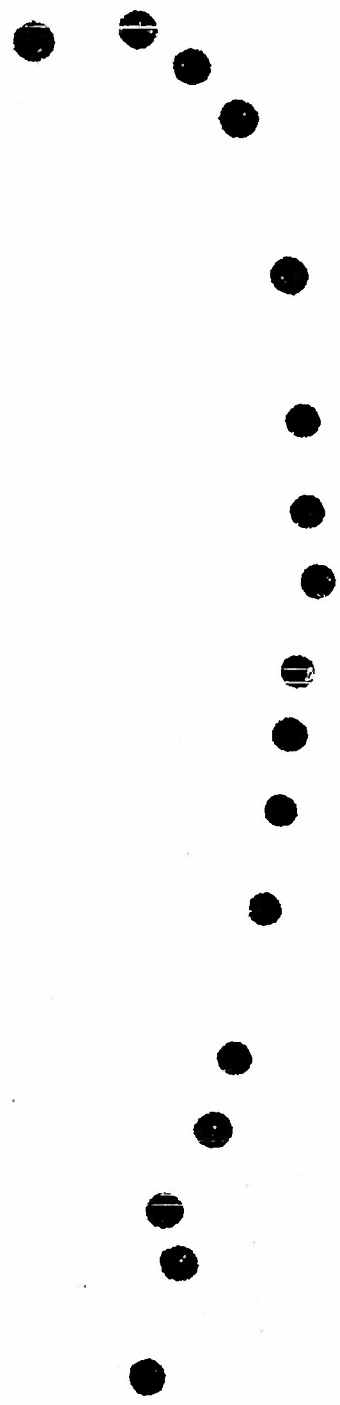

Fig. 2 Imprints of drops on an ammonium chloride coated slide. These drops represent those ejected to the greatest height when bubbles of 450 microns diameter break at an air-water interface. (See the top trajectory of figures 1a and 1b).

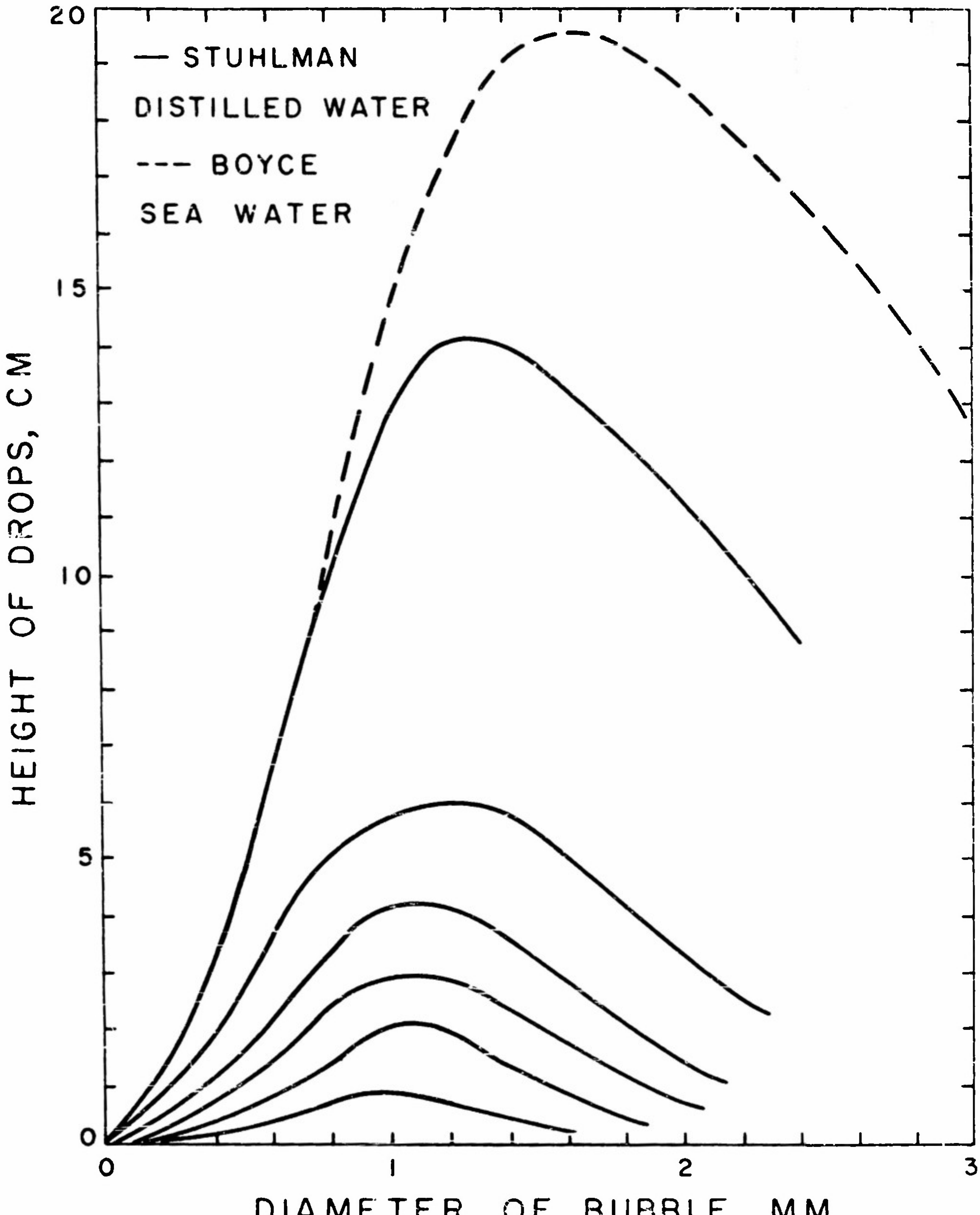

Fig. 3 The height of ejection of drops from breaking bubbles as a function of the bubble diameter. The solid lines are obtained by Stuhlman (7) who observed six drops produced when a bubble breaks in distilled water and the single dashed line was obtained by Boyce (9). This latter measurement is for the maximum ejected height for drops produced by bubbles breaking in sea water.

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